Getting around in the Arctic
– what we do (and don't) know about boundary currents

Rebecca Woodgate
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What have we got to go on?

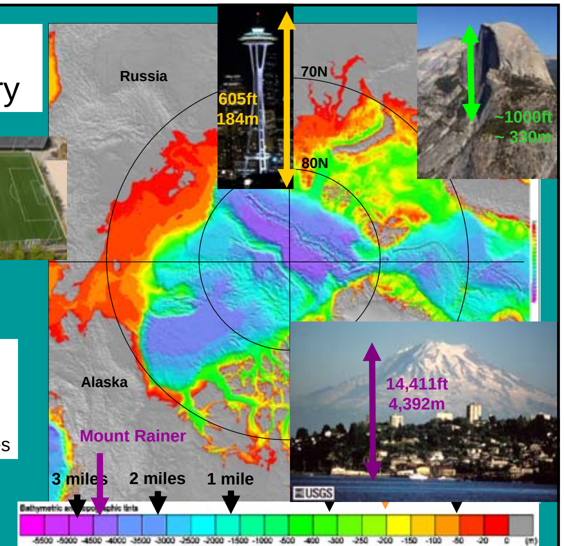
The Arctic plumbing diagram
- how do we know it?
- how good is it?

(Pacific Water Shelf Break (boundary) Currents)

The Arctic Ocean Boundary Current

How else can we move?

Arctic Bathymetry



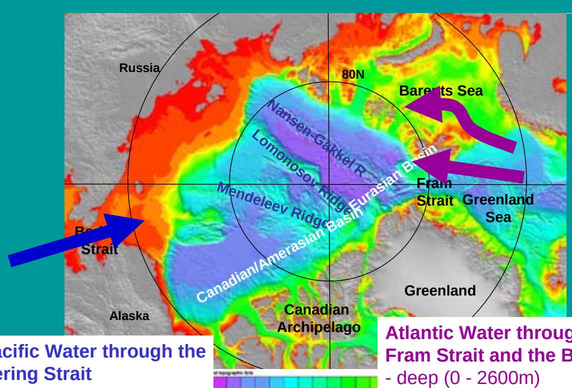
Broad shelves

Deep Basins

Mid-ocean Ridges

IBCAO (International Bathymetric Chart of the Arctic Ocean)

INFLOWS

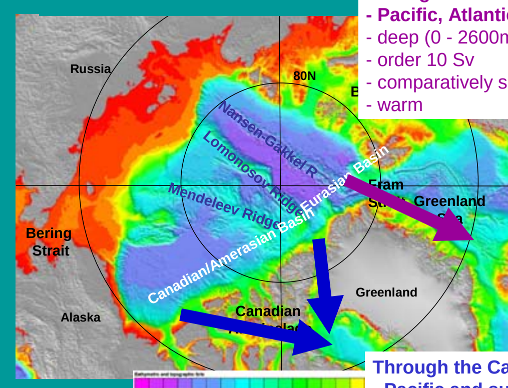


Pacific Water through the Bering Strait
- shallow (0 - 50m)
- order 1 Sv
- comparatively fresh
- seasonally warm/cold

Atlantic Water through the Fram Strait and the Barents Sea
- deep (0 - 2600m)
- order 10 Sv
- comparatively salty
- warm

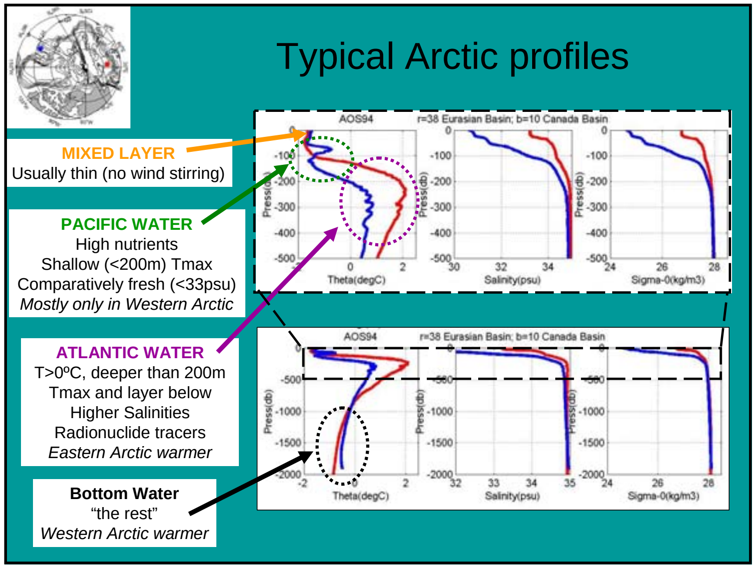
OUTFLOWS

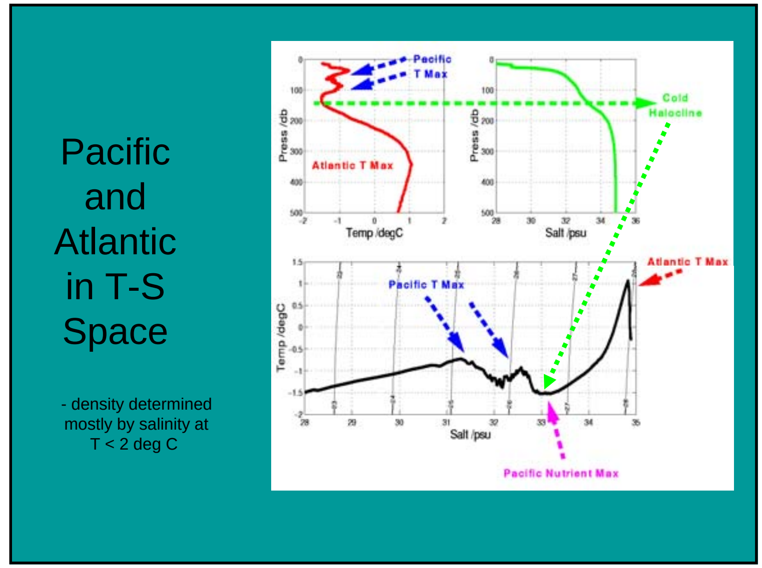
Through Fram Strait
- Pacific, Atlantic and surface waters
- deep (0 - 2600m)
- order 10 Sv
- comparatively salty
- warm

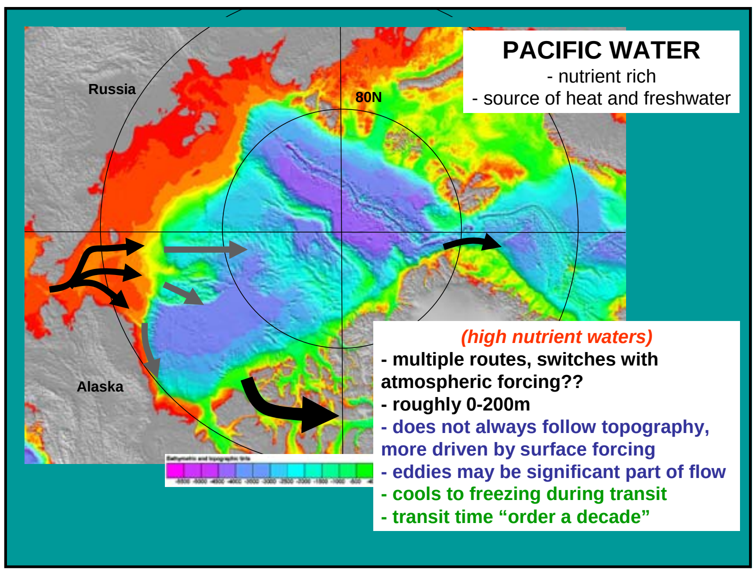


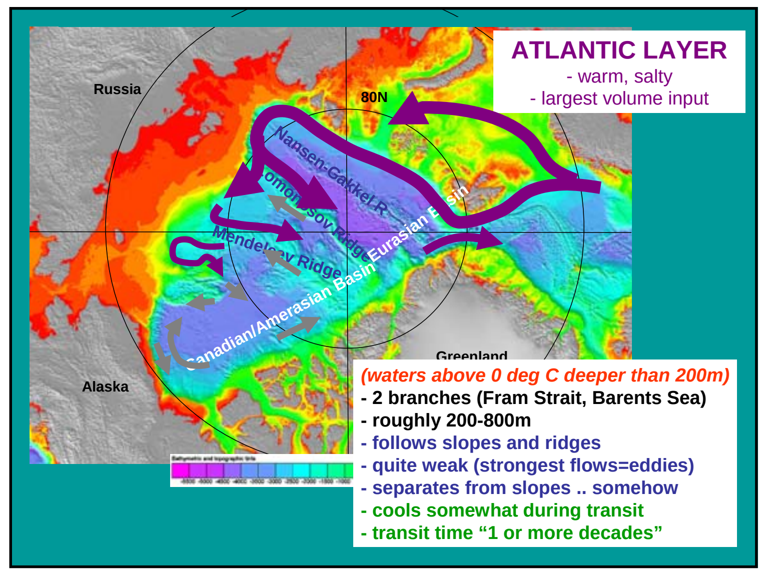
- All into Atlantic
(Some short term southward flow through the Bering Strait)

Through the Canadian Archipelago
- Pacific and surface waters
- shallow (0 – few hundred m)
- order 1 Sv
- comparatively fresh


Typical Arctic profiles
MIXED LAYER
Usually thin (no wind stirring)
PACIFIC WATER
High nutrients
Shallow (<200m) Tmax
Comparatively fresh (<33psu)
Mostly only in Western Arctic
ATLANTIC WATER
T>0ºC, deeper than 200m
Tmax and layer below
Higher Salinities
Radionuclide tracers
Eastern Arctic warmer
Bottom Water
“the rest”
Western Arctic warmer
AOS94
r=38 Eurasian Basin; b=10 Canada Basin
Theta(degC)
Salinity(psu)
Sigma-0(kg/m3)
Press(db)

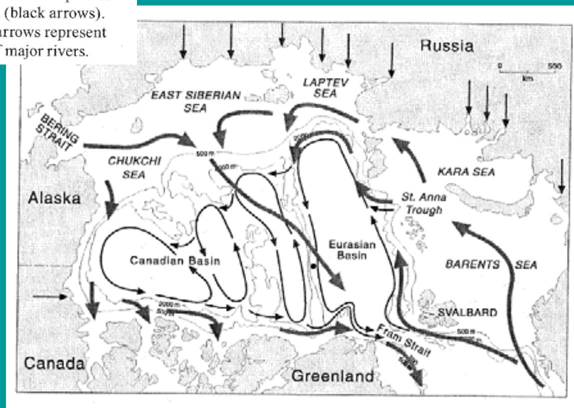

Pacific
and
Atlantic
in T-S
Space
- density determined
mostly by salinity at
T < 2 deg C
Pacific
T Max
Atlantic T Max
Cold
Halocline
Temp /degC
Salt /psu
Press /db
Pacific T Max
Atlantic T Max
Pacific Nutrient Max


PACIFIC WATER
- nutrient rich
- source of heat and freshwater
Russia
80N
Alaska
(high nutrient waters)
- multiple routes, switches with
atmospheric forcing??
- roughly 0-200m
- does not always follow topography,
more driven by surface forcing
- eddies may be significant part of flow
- cools to freezing during transit
- transit time “order a decade”


ATLANTIC LAYER
- warm, salty
- largest volume input
Russia
80N
Alaska
Greenland
Nansen-Gakkel R
Lomonosov Ridge
Mendeleev Ridge
Eurasian Basin
Canadian/Amerasian Basin
(waters above 0 deg C deeper than 200m)
- 2 branches (Fram Strait, Barents Sea)
- roughly 200-800m
- follows slopes and ridges
- quite weak (strongest flows=eddies)
- separates from slopes .. somehow
- cools somewhat during transit
- transit time “1 or more decades”

Arctic Plumbing

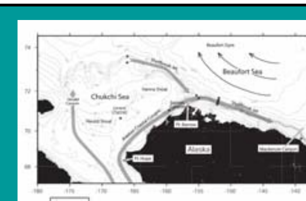
Fig. 2. Schematic circulation of surface water (grey arrows) and the Atlantic Layer plus Upper Polar Deep Water to depths of about 1700 m (black arrows). The straight arrows represent the mouths of major rivers.

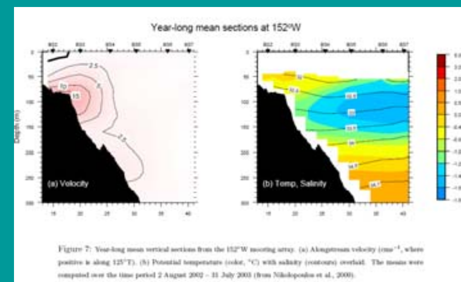


AW circulation very different to PW circulation
- AW follows topography (with exceptions?)
- PW follows ice ??

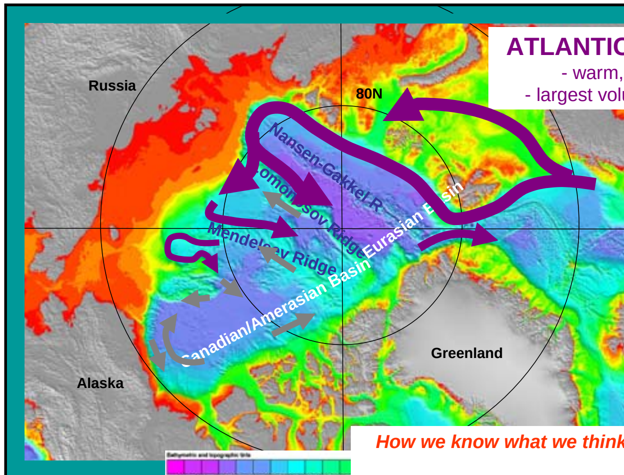
Jones et al., 2001, Polar Research

Pacific Water Shelf Break jet





Pickart et al, submitted, 2010



ATLANTIC LAYER
- warm, salty
- largest volume input

How we know what we think we know

What we think we know

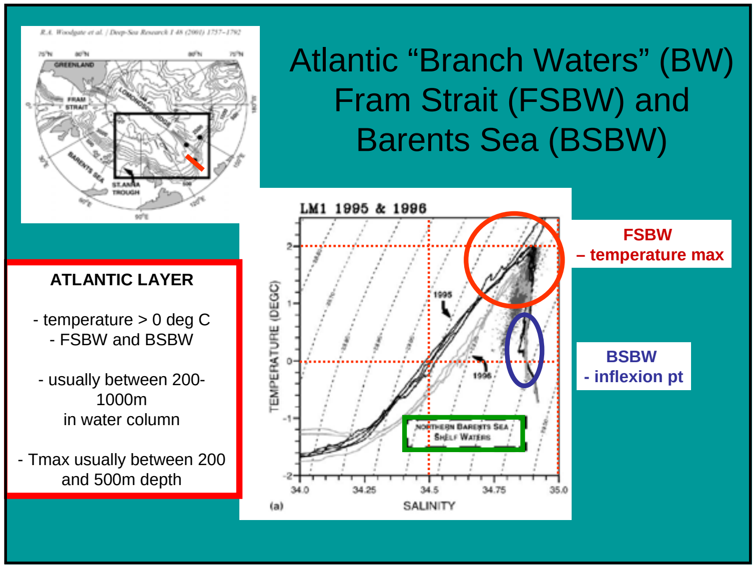
Some possible explanations

General AW Circulation Schemes

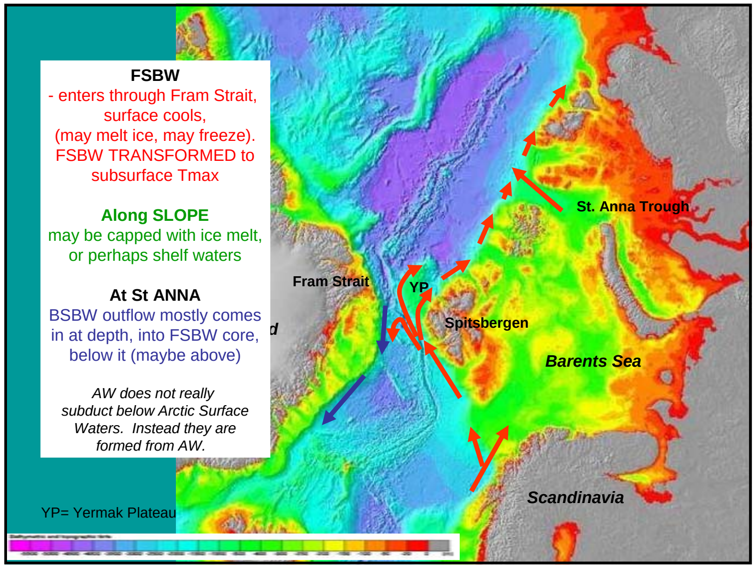
Fig. 9. Schematic diagram showing the inferred circulation in the Arctic Ocean of the Atlantic Layer and intermediate depth waters, between 200 m and 1700 m.

Aagaard, 1989
- topographically steered boundary current along slopes and ridges
- interior flow weak, dominated by eddies
(based on current meters)

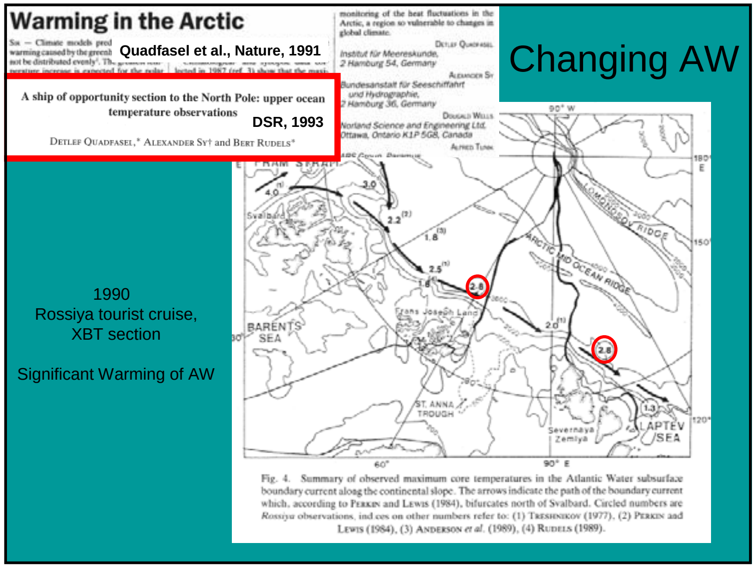
Rudels et al, 1994
- mixing off St Anna
- cyclonic (anti-clockwise) circulation
(based on T-S and tracers)



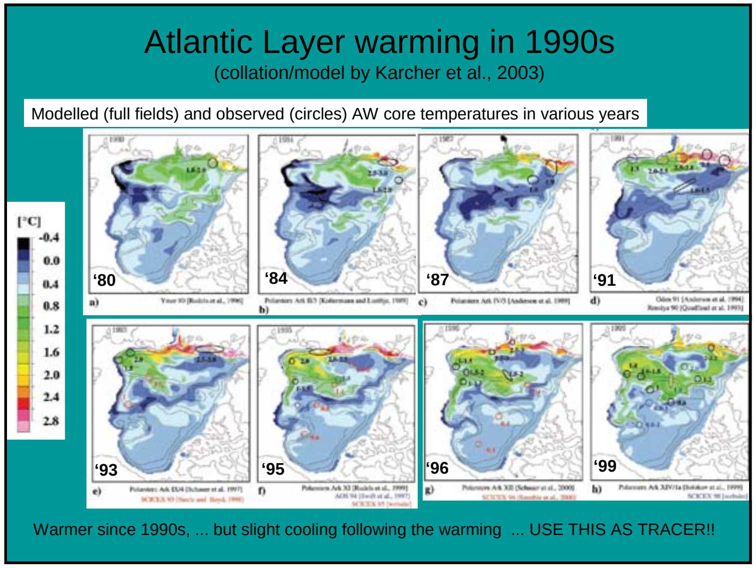
Atlantic "Branch Waters" (BW) Fram Strait (FSBW) and Barents Sea (BSBW)
ATLANTIC LAYER
- temperature > 0 deg C
- FSBW and BSBW
- usually between 200-1000m in water column
- Tmax usually between 200 and 500m depth
LM1 1995 & 1996
TEMPERATURE (DEGC)
SALINITY
NORTHERN BARENTS SEA SHELF WATERS
FSBW – temperature max
BSBW - inflexion pt



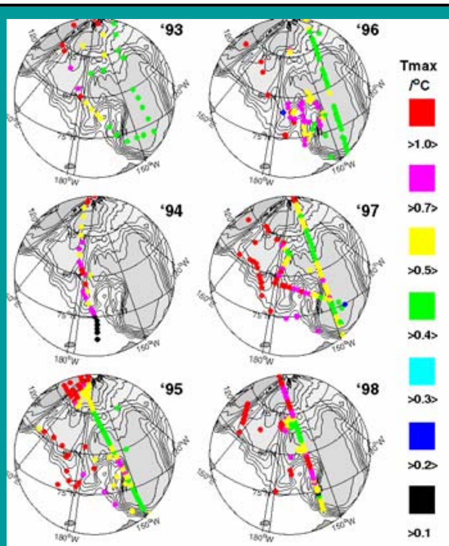
FSBW
- enters through Fram Strait, surface cools, (may melt ice, may freeze). FSBW TRANSFORMED to subsurface Tmax
Along SLOPE
may be capped with ice melt, or perhaps shelf waters
At St ANNA
BSBW outflow mostly comes in at depth, into FSBW core, below it (maybe above)
AW does not really subduct below Arctic Surface Waters. Instead they are formed from AW.
YP= Yermak Plateau
Fram Strait
YP
Spitsbergen
St. Anna Trough
Barents Sea
Scandinavia



Warming in the Arctic
Quadfasel et al., Nature, 1991
A ship of opportunity section to the North Pole: upper ocean temperature observations
DSR, 1993
Detlef Quadfasel, Alexander Sy and Bert Rudels
Changing AW
1990
Rossiya tourist cruise, XBT section
Significant Warming of AW
BARENTS SEA
ST. ANNA TROUGH
LAPTEV SEA
Severnaya Zemlya
Franz Joseph Land
Svalbard
Fig. 4. Summary of observed maximum core temperatures in the Atlantic Water subsurface boundary current along the continental slope. The arrows indicate the path of the boundary current which, according to Perkin and Lewis (1984), bifurcates north of Svalbard. Circled numbers are Rossiya observations, ind ces on other numbers refer to: (1) Treshnikov (1977), (2) Perkin and Lewis (1984), (3) Anderson et al. (1989), (4) Rudels (1989).



Atlantic Layer warming in 1990s
(collation/model by Karcher et al., 2003)
Modelled (full fields) and observed (circles) AW core temperatures in various years
[°C]
-0.4
0.0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
'80
'84
'87
'91
'93
'95
'96
'99
Warmer since 1990s, ... but slight cooling following the warming ... USE THIS AS TRACER!!



AW warming spreads also into Western Arctic

Tmax from submarine cruises

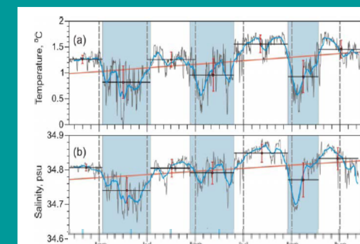
See warming, but data very sparse

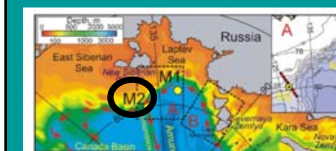
Woodgate et al, 2001, NSF proposal

Seasonal Atlantic Water Variability

Dmitrenko et al, in press

~260 m, i.e. Fram Strait Branch

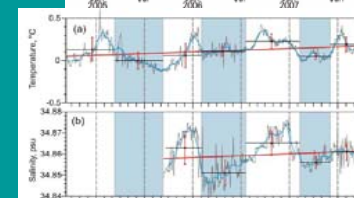




- amplitude ~ 0.5 deg C!!

- aliasing problems with CTD sections

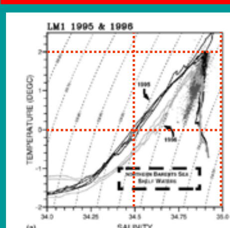
- different timing at depth



~ 840 m, i.e. Barents Sea Branch

Tracers of Atlantic Water

TEMPERATURE-SALINITY
- presence of Tmax
- form in TS space
- following a warming



- also dissolved oxygen??
- Delta O18?? (not really)
- N:P ratios (perhaps)

NON-CONSERVATIVE (weakness and strength)

CHEMICAL TRACERS
- usually atmospheric source
- mixed into surface water, and then isolated from the atmosphere

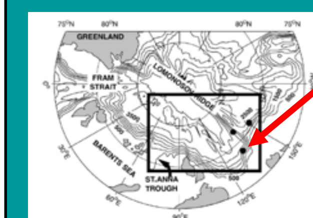
CFCs (ChloroFluoroCarbons)
- solvents from 1960s onwards
- CCl4 ("carbon-tet") is oldest then CFC11, CFC12 and newest CFC113
- atmospheric concentrations KNOWN
- use presence or ratios to give age

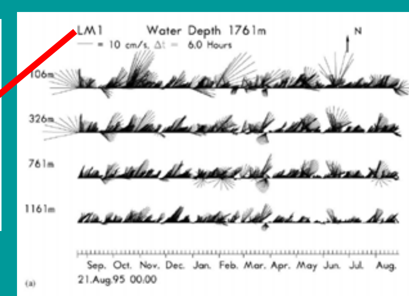
Cs and I from Nuclear Reprocessing
- on-going,
- concentrations KNOWN
- use presence or ratios to give age

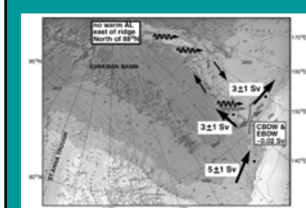
Bomb Tritium
- atomic bomb tests 1950s
- surface layer of tritium (isotope of H)
- decays to Helium-3 (half-life ~ 12.4 yrs)

CONSERVATIVE - but mixing important

Bringing it back to observations







- Equivalent barotropic Flow Structure
- mean ~ few cm/s, plus stronger eddies
- 5 ± 1 Sv split into 2 by the Lomonosov ridge
- found over 500-3000m depth contours
- 50-100km wide

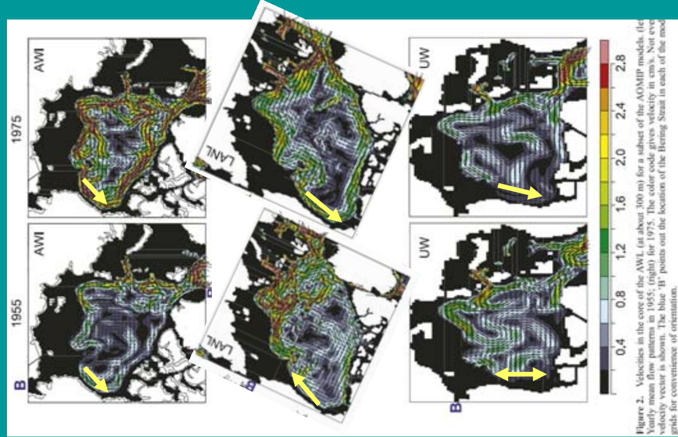
Woodgate et al, 2001

.. also in models

Karcher et al., 2007
- 3 of the "best" Arctic models

1975

1955



.. state-of-the-art models are inconsistent about direction of circulation in the Western Arctic!!

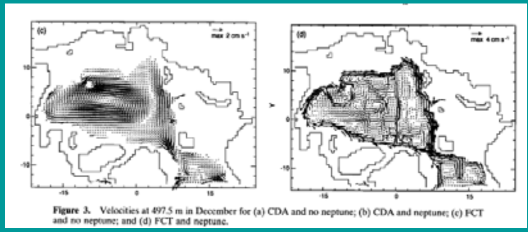
What drives the Boundary Current?

PROPERTIES TO EXPLAIN:
- equivalent barotropic structure
- steered by topography - weak
- variability NOT local - width (~ 100 km)

???
- pathways - variability -direction

Greg Holloway "Neptune" effect
(Holloway, 1987; Nazarenko et al, 1998)

Eddy-topography interactions drive a mean along isobath flow



- makes model look like our bias, .. BUT IS TUNED
- can we quantify this effect given number of eddies?
- "topostrophy" = "v x grad D" = tendency of flow to follow topog (Holloway et al, 2007)

Taking things down to "basics"

Barotropic

Fully non-linear model, 7.5km resolution

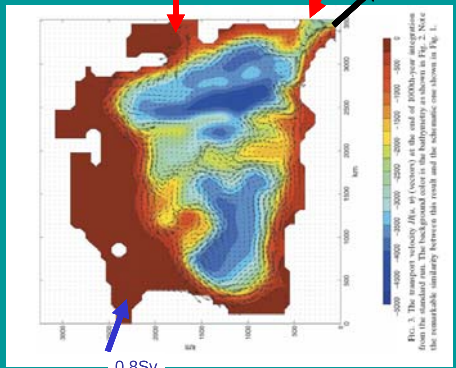
Constant in and out flows

No surface forcing

1.2Sv

2.0Sv

4 Sv



0.8Sv

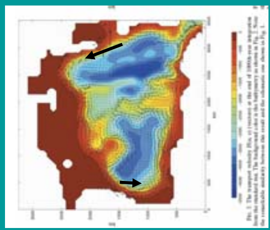
Yang, 2005

PV of inflows?

The Arctic and Subarctic Ocean Flux of Potential Vorticity and the Arctic Ocean Circulation

JIAYAN YANG

JPO, 2005



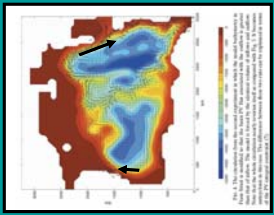


TABLE 1. Arctic and subarctic ocean fluxes in the standard run.

	PV flux ($m^2 s^{-2}$)	Volume flux (Sv)	Sill depth (m)
Bering Strait inflow	1.078	0.8	100
Barents Sea inflow	0.796	2.0	369
Fram Strait inflow	0.109	1.2	1797
Fram Strait outflow	−0.200	−4.0	2795
Total	1.7830	0.0	

+ve PV total = cyclonic flow

TABLE 2. Arctic and subarctic ocean fluxes in the modified topography run.

	PV flux ($m^2 s^{-2}$)	Volume flux (Sv)	Sill depth (m)
Bering Strait inflow	1.078	0.8	100
Barents Sea inflow	0.796	2.0	369
Fram Strait inflow	1.058	1.2	162
Fram Strait outflow	4.544	−4.0	128
Total	−1.612	0.0	

-ve PV total = anticyclonic flow

Cyclonic/Anticyclonic depends on Potential Vorticity balance of in and out flows

Get niggly about the details
- sill depths
- missing Canadian Archipelago
- not Barotropic if including Pacific Water

BUT ...

TABLE 1. Arctic and subarctic ocean fluxes in the standard run.

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Fram Strait outflow	−0.200	−4.0	2795
Total	1.7830	0.0	

Yang, 2005

PV Flux = Transport x PV where PV is $\left(\frac{f+\zeta}{H}\right)$

So – Bering Strait and Canadian Archipelago balance approximately
- What goes in Fram Strait, comes out

Difference lurks in Barents Sea flux, which comes in as shallow water column (PV high) and goes out as a deep water column (PV low)

THUS – expect incoming PV higher than outgoing PV - thus cyclonic

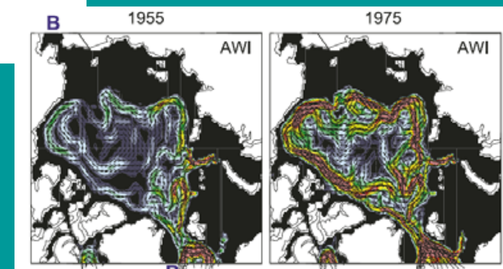
But .. there is also a PV source from surface stress

Karcher et al, 2007

Primitive equation model, within an Atlantic water density layer

In Eurasian Basin
- PV forcing from Barents

In Canadian Basin
- surface PV forcing



Bringing it back to f/H contours

Nost and Isachsen, 2003

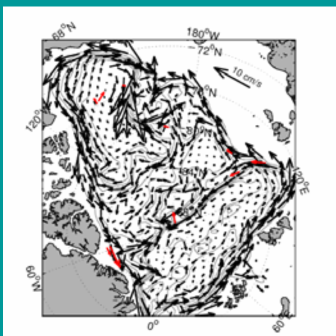
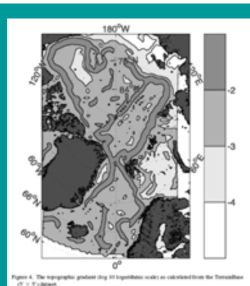


Figure 12. Modeled bottom geostrophic velocities (black arrows) and observed near bottom currents (red arrows) for the Arctic Ocean. The sources of the observed near bottom currents are Newton and Coachman (1974) (Canada Basin), Newton and Sotirin (1997) (Lincoln Sea), Aagaard (1981) (Lomonosov Ridge near the North Pole), Woodgate *et al.* (2001) (the three current meter moorings near 140W, 80N).

Black = modeled, Red = observations

Simple theory, Ekman pumping and hydrographic forcing from climatology

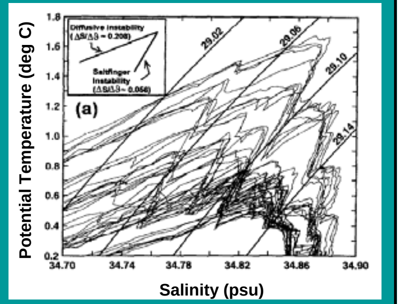
Boundary Current
- topographically steered
- forced by wind stress from Nordic Seas



Atlantic Water zigzags AOS94

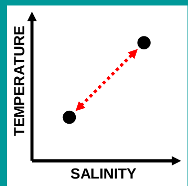
Line up/ Nest all through the Arctic - ~ 5,000km

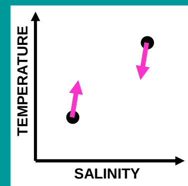
Angles of the Zigzags match double diffusive theory



Carmack et al, 1997

Mixing and Double Diffusion in T-S Space

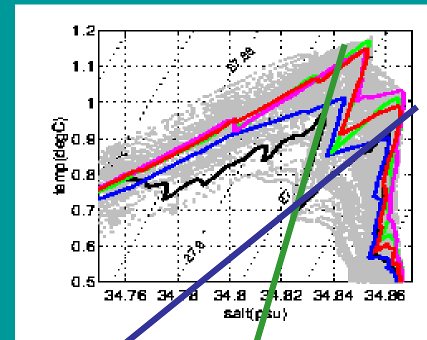




Mechanical mixing in TS space creates straight lines between water masses

In double diffusive processes, heat diffuses faster than salt.

So, in TS space resultant waters are not on a straight line between the parent water masses



Theories for formation, and for growing to a large amplitude steady state
(Turner, Ruddick, Toole, Georgi, McDougall, Walsh, Carmack, Rudels, May …)

Diffusive Convection Regime
Cold Fresh / Warm Salty
unstable in temperature

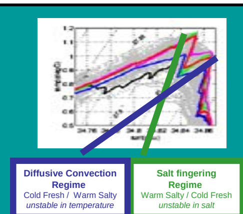
Salt fingering Regime
Warm Salty / Cold Fresh
unstable in salt

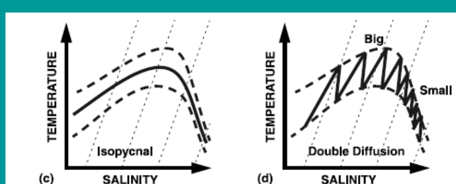
Temperature unstable

Salinity unstable

"T-S Zigzags" in the Arctic

Interaction of two water columns
- therefore can learn something about origins





Line up throughout Arctic (~ 5000km)
- therefore LOW ENERGY environment

Spread by??
- self propagating? (spread at 90deg to front)
- fossil intrusions? (carried advectively)

Can be used as a tracer of the boundary current???

Many refs,
- most Carmack, Walsh or McDougal
for overview, see Woodgate et al, 2007

The Warming of the 1990s

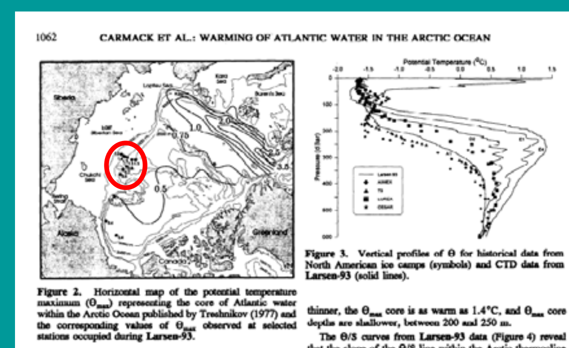

1062 CARMACK ET AL.: WARMING OF ATLANTIC WATER IN THE ARCTIC OCEAN

Figure 2. Horizontal map of the potential temperature maximum (Θ_{max}) representing the core of Atlantic water within the Arctic Ocean published by Treshnikov (1977) and the corresponding values of Θ_{max} observed at selected stations occupied during Larsen-93.

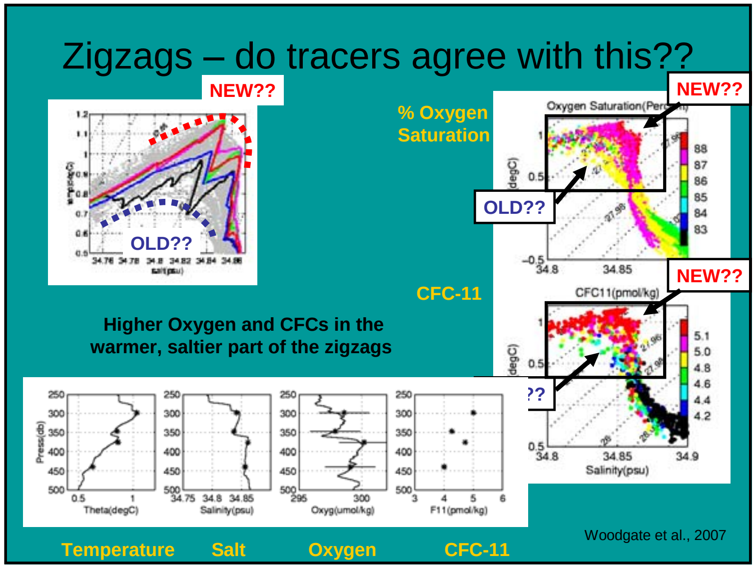
Figure 3. Vertical profiles of Θ for historical data from North American ice camps (symbols) and CTD data from Larsen-93 (solid lines).

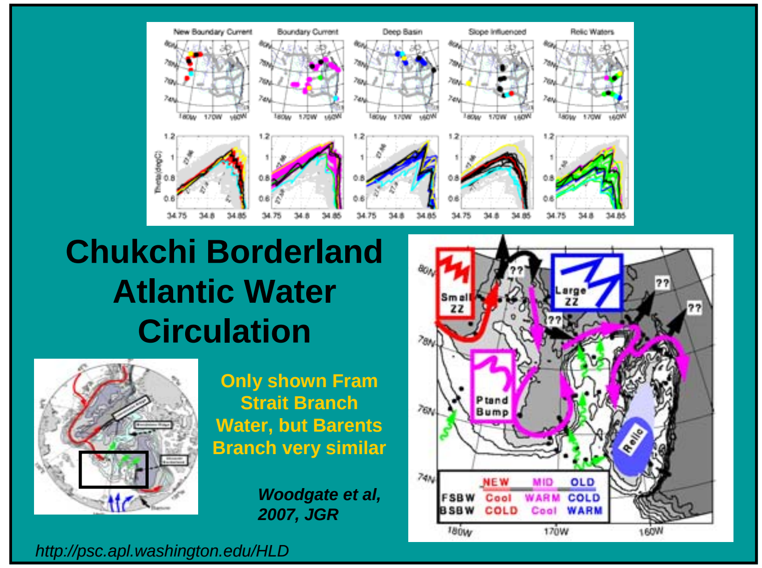
thinner, the Θ_{max} core is as warm as 1.4°C, and Θ_{max} core depths are shallower, between 200 and 250 m.

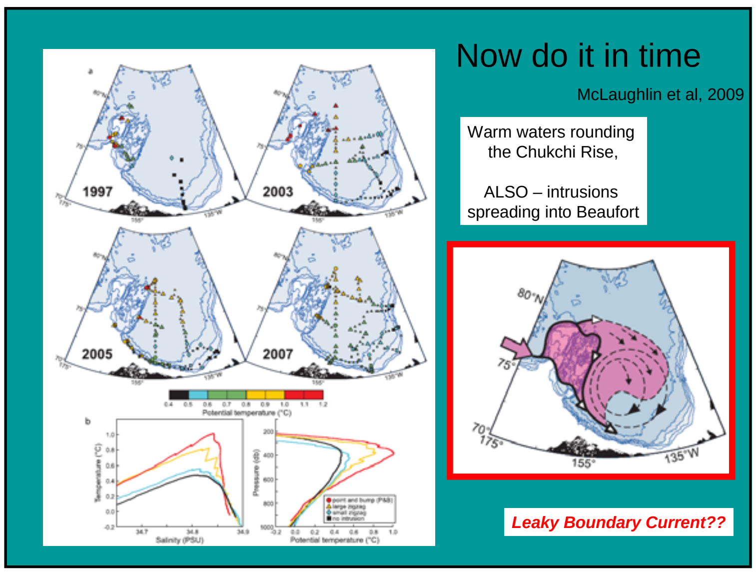
The Θ/S curves from Larsen-93 data (Figure 4) reveal that the slope of the Θ/S line within the Arctic thermocline

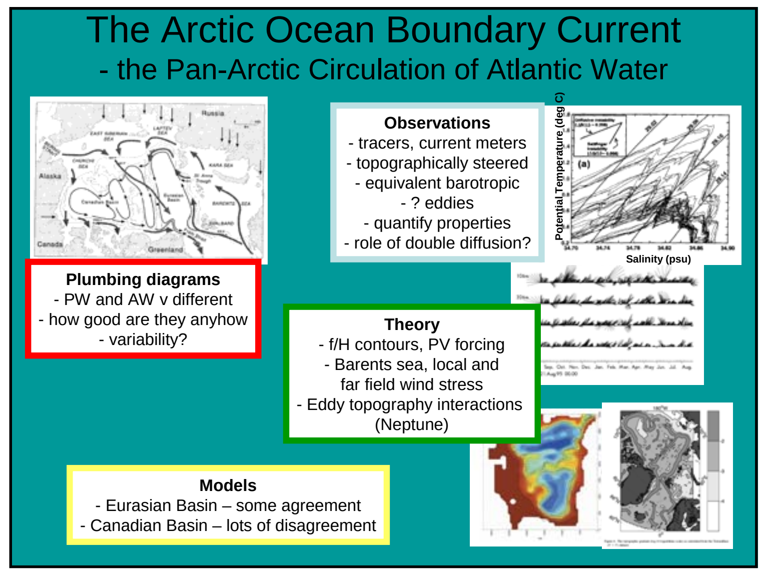
1993 Larsen
- **1 deg warmer on the Mendeleev Ridge**
- **inversions in temperature and salinity**

Carmack et al, '95, and McLaughlin et al, '96


Zigzags – do tracers agree with this??
NEW??
OLD??
% Oxygen Saturation
Oxygen Saturation(Percent)
NEW??
OLD??
CFC-11
CFC11(pmol/kg)
NEW??
??
Salinity(psu)
Higher Oxygen and CFCs in the warmer, saltier part of the zigzags
Press(db)
Theta(degC)
Salinity(psu)
Oxyg(umol/kg)
F11(pmol/kg)
Woodgate et al., 2007
Temperature
Salt
Oxygen
CFC-11


New Boundary Current
Boundary Current
Deep Basin
Slope Influenced
Relic Waters
Chukchi Borderland Atlantic Water Circulation
Only shown Fram Strait Branch Water, but Barents Branch very similar
Woodgate et al, 2007, JGR
Small ZZ
Large ZZ
??
Ptand Bump
Relic
NEW
MID
OLD
FSBW
Cool
WARM
COLD
BSBW
COLD
Cool
WARM
http://psc.apl.washington.edu/HLD


Now do it in time
McLaughlin et al, 2009
1997
2003
2005
2007
Warm waters rounding the Chukchi Rise,
ALSO – intrusions spreading into Beaufort
Potential temperature (°C)
Salinity (PSU)
Leaky Boundary Current??


The Arctic Ocean Boundary Current
- the Pan-Arctic Circulation of Atlantic Water
Observations
- tracers, current meters
- topographically steered
- equivalent barotropic
- ? eddies
- quantify properties
- role of double diffusion?
Potential Temperature (deg C)
Salinity (psu)
Plumbing diagrams
- PW and AW v different
- how good are they anyhow
- variability?
Theory
- f/H contours, PV forcing
- Barents sea, local and far field wind stress
- Eddy topography interactions (Neptune)
Models
- Eurasian Basin – some agreement
- Canadian Basin – lots of disagreement